$\Delta\Gamma_d$: A Forgotten Null Test of the Standard Model

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The recent measurement of an anomalous like-sign dimuon asymmetry by the D0 collaboration has prompted theoretical speculation on possible sources of physics beyond the Standard Model that may affect lifetimes and lifetime differences in neutral B meson systems. One observable that deserves closer attention is the width difference in the B_d^0 system, $\Delta\Gamma_d$. Since the Standard Model prediction for this quantity is well below 1 %, it serves as a "null test" whereby the measurement of a larger value would cleanly reveal the presence of new physics. Methods to measure $\Delta\Gamma_d$ at current and future experiments are reviewed and an attractive new approach is proposed.

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Recently, the D0 collaboration have measured an anomalous like-sign dimuon asymmetry [1, 2], which could originate from CP violation effects in either or both of the B_d^0–$\bar{B}_d^0$ and B_s^0–$\bar{B}_s^0$ systems. Since the Standard Model (SM) predictions for CP violation in mixing in both systems are $\mathcal{O}(10^{-3})$ or smaller [3], a significant effect at the percent level would be a clear signal of non-SM contributions. When combined with other constraints on CP violation in B_d^0–$\bar{B}_d^0$ [4, 5] and B_s^0–$\bar{B}_s^0$ [6] mixing, it appears most likely that the effect is not solely due to either neutral meson system alone, but rather that anomalous CP violation effects may be manifest in both [1, 2, 7]. Despite the many experimental studies of the B_d^0 system over the past decade, the possibility of such effects is not ruled out (see for example Ref. [8] and references therein).

Although improved experimental measurements are certainly necessary, the D0 result has prompted a great deal of theoretical speculation on sources of physics beyond the Standard Model ("new physics") that could be responsible for the effect. One interesting possibility is that new physics may cause the neutral B meson lifetimes and lifetime differences to differ from their SM values [9–12]. Such scenarios – in particular the possibility that the width differences $\Delta\Gamma_q$ ($q = d, s$) between the eigenstates of the effective weak Hamiltonian in the B_q^0–$\bar{B}_q^0$ systems may be enhanced above their SM values – have not previously been widely considered. In particular, with little exception [13, 14], the utility of $\Delta\Gamma_d$ to test the SM has been largely overlooked.

To test new physics models that affect $\Delta\Gamma_q$ it is necessary to have improved measurements of the parameters of the neutral B meson systems, and to have precise SM predictions to compare against. A useful class of tests is those referred to as "null tests", in which the Standard Model prediction is vanishingly small compared to the experimental sensitivity. The search for CP violation in neutral B meson mixing itself falls into this class of tests. Among the CP-conserving mixing parameters, however, there is also one parameter which is very small in the SM, namely $\Delta\Gamma_d$, for which the prediction is [3]

$$\frac{\Delta\Gamma_d^{\rm SM}}{\Delta M_d^{\rm SM}} = \left(52.6\,^{+11.5}_{-12.8}\right) \times 10^{-4}\,, \tag{1}$$

$$\Delta\Gamma_d^{\rm SM} = \left(26.7\,^{+5.8}_{-6.5}\right) \times 10^{-4}\ {\rm ps}^{-1}\,, \tag{2}$$

$$\frac{\Delta\Gamma_d^{\rm SM}}{\Gamma_d^{\rm SM}} = \left(40.9\,^{+8.9}_{-9.9}\right) \times 10^{-4}\,, \tag{3}$$

where the second and third results are obtained using the experimental values of the mass difference and average lifetime in the B_d^0–$\bar{B}_d^0$ system, $\Delta M_d^{\rm exp} = (0.507 \pm 0.004)\ {\rm ps}^{-1}$ and $1/\Gamma_d^{\rm exp} = \tau(B_d^0)^{\rm exp} = (1.530 \pm 0.009)$ ps [15]. This involves an assumption that there are no new physics contributions to $\Delta M_d^{\rm exp}$ and $\Gamma_d^{\rm exp}$, *i.e.* that $\Delta M_d^{\rm exp} = \Delta M_d^{\rm SM}$ and $\Gamma_d^{\rm exp} = \Gamma_d^{\rm SM}$. The former is indeed confirmed to good precision by global fits to the Cabibbo-Kobayashi-Maskawa (CKM) [16, 17] Unitarity Triangle (see, for example, Refs. [18] and [19]). In any case, plausible new physics effects in the values of ΔM_d and Γ_d cannot change the conclusion that $\Delta\Gamma_d^{\rm SM}/\Gamma_d^{\rm SM} \ll \mathcal{O}(10^{-2})$.

It is striking that there are relatively few measurements of $\Delta\Gamma_d$ listed by the Particle Data Group [15] and the Heavy Flavour Averaging Group [20]. The world average, based mainly on a single measurement from BaBar [21, 22] is ${\rm sign}({\rm Re}\,\lambda_{CP})\Delta\Gamma_d/\Gamma_d = 0.009 \pm 0.037$. BaBar use a notation in which ${\rm sign}({\rm Re}\,\lambda_{CP})$ is expected to be +1 in the SM (where it is, to a good approximation, equal to ${\rm sign}(\cos 2\beta)$, where β is one of the CKM Unitarity Triangle angles). As discussed below, $\Delta\Gamma_d$ may be quite challenging to measure, but nevertheless its determination should be possible for the existing B-factory experiments, BaBar [23] and Belle [24], the Tevatron experiments CDF [25] and D0 [26], the CERN LHCb experiment [27] and any future Super Flavour Factory [28–30]. Even discounting any potential sensitivity to new physics, $\Delta\Gamma_d$ is a fundamental parameter of the neutral B meson system and should be measured as precisely as possible.

As a brief digression, it is interesting to consider the situation in the D^0–$\bar{D}^0$ system (see Ref. [31] for a de-

tailed review). Before the first evidence of charm oscillations was discovered in 2007 [32, 33], the SM values of the mixing parameters $x_D = \Delta m_D/\Gamma_D$ and $y_D = \Delta\Gamma_D/2\Gamma_D$ were generally believed to be $\mathcal{O}(10^{-3})$. However, theoretical re-evaluations have shown that values as large as the experimental measurements, which are $\mathcal{O}(10^{-2})$, cannot be ruled out within the Standard Model. To resolve the situation, more precise measurements and improved theoretical calculations are required. The theoretical situation for the neutral B mesons is, however, somewhat better compared to that for charm mesons, due to the different regime with regard to QCD effects.

In order to examine how $\Delta\Gamma_d$ may be determined experimentally, consider the time-dependent decay rates of a neutral B meson that is initially (at time $\Delta t = 0$) tagged as $\bar{B}^0_q$ or B^0_q to a final state f. Assuming CPT conservation, and neglecting corrections arising from CP violation in mixing (discussed further below), these are given by [34]

$$\Gamma_{\bar{B}^0_q\to f}(\Delta t) = \mathcal{N}_f \frac{e^{-|\Delta t|/\tau(B^0_q)}}{4\tau(B^0_q)} \left[\cosh\left(\frac{\Delta\Gamma_q\Delta t}{2}\right) + S_f\sin(\Delta m_q\Delta t) - C_f\cos(\Delta m_q\Delta t) + \mathcal{A}^{\Delta\Gamma}_f \sinh\left(\frac{\Delta\Gamma_q\Delta t}{2}\right)\right], \quad (4)$$

$$\Gamma_{B^0_q\to f}(\Delta t) = \mathcal{N}_f \frac{e^{-|\Delta t|/\tau(B^0_q)}}{4\tau(B^0_q)} \left[\cosh\left(\frac{\Delta\Gamma_q\Delta t}{2}\right) - S_f\sin(\Delta m_q\Delta t) + C_f\cos(\Delta m_q\Delta t) + \mathcal{A}^{\Delta\Gamma}_f \sinh\left(\frac{\Delta\Gamma_q\Delta t}{2}\right)\right], \quad (5)$$

where

$$S_f = \frac{2\,\mathrm{Im}(\lambda_f)}{1+|\lambda_f|^2}, \qquad C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}, \quad (6)$$

$$\mathcal{A}^{\Delta\Gamma}_f = -\frac{2\,\mathrm{Re}(\lambda_f)}{1+|\lambda_f|^2}, \text{ and } \lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f}. \quad (7)$$

Note that $(S_f)^2 + (C_f)^2 + \left(\mathcal{A}^{\Delta\Gamma}_f\right)^2 = 1$ by definition. The parameters $\bar{A}_f$ and A_f are the complex amplitudes for the decay of a $\bar{B}^0_q$ and a B^0_q to the final state f, respectively. The parameters q and p describe the eigenstates of the effective weak Hamiltonian of the B^0_q–$\bar{B}^0_q$ system (in the absence of CP violation in mixing, $|q/p| = 1$). The constant $\mathcal{N}_f$ is a normalisation factor. The equations above are identical for B meson production in any environment, but in coherent production of $B\bar{B}$ pairs at e^+e^- B factory colliders the quantum entanglement allows flavour tagging at any time so that the range of Δt is $-\infty < \Delta t < \infty$, whereas B mesons produced in hadron collisions (or at higher energy e^+e^- colliders) are tagged at their production point ($0 < \Delta t < \infty$). Note that in contrast to the CP-violating asymmetry parameters S_f and C_f, the parameter $\mathcal{A}^{\Delta\Gamma}_f$ appears with the same sign in both $\bar{B}^0_q$ and B^0_q decay time distributions.

Focussing now on the B^0_d system, and assuming that $y_d = \Delta\Gamma_d/2\Gamma_d \ll 1$, the following substitutions can be made

$$\cosh\left(\frac{\Delta\Gamma_d\Delta t}{2}\right) \approx 1, \quad (8)$$

$$\sinh\left(\frac{\Delta\Gamma_d\Delta t}{2}\right) \approx y_d\,\tau(B^0_d)\,\Delta t, \quad (9)$$

where terms of $\mathcal{O}(y_d^2)$ have been neglected. The best channels to measure $\Delta\Gamma_d$ with are therefore those with large branching fractions and large, well-known values of $\mathcal{A}^{\Delta\Gamma}_f$. Experimentally, it is also desirable to use final states that are advantageous from the point of view of minimising systematic errors – specifically, those with relatively clean signals and with accessible control samples with similar topologies. These considerations suggest that decays mediated by the $b \to c\bar{c}s$ quark-level transition and involving J/ψ mesons in the final state will be most suitable.

Since the term involving $\mathcal{A}^{\Delta\Gamma}_f$ is the same for $\bar{B}^0_d$ and B^0_d decays, y_d can be determined in untagged analyses (*i.e.* without determining the initial flavour of the decaying B meson). With the approximations above, the untagged decay rate is

$$\Gamma_{\bar{B}^0_d\to f}(\Delta t) + \Gamma_{B^0_d\to f}(\Delta t) \propto e^{-|\Delta t|/\tau(B^0_d)}\left(1 + \mathcal{A}^{\Delta\Gamma}_f y_d\,\tau(B^0_d)\,\Delta t\right). \quad (10)$$

Noting that $e^{X(1+\epsilon)} \approx e^X(1+X\epsilon)$, this result shows that (i) the effect of $y_d \neq 0$ is that the effective lifetimes measured in decays to different final states (with different values of $\mathcal{A}^{\Delta\Gamma}_f$) can differ; (ii) any attempt to measure y_d from a single final state will suffer from large systematic uncertainties.

Bearing this in mind, there are four main possible approaches that can be used to determine y_d.

1. *From the difference in effective lifetime between decays to CP-eigenstates and decays to flavour-specific (or quasi-flavour-specific) final states.*

This is the approach used by BaBar [21, 22], where the CP-eigenstate sample is dominated by $J/\psi\, K^0_S$, and the quasi-flavour-specific sample is dominated by $D^{(*)-}h^+$ ($h = \pi, \rho, a_1$). Semileptonic decays ($D^{(*)-}l^+\nu$) have

also been proposed as a high-statistics flavour-specific control sample [13]. Flavour-specific final states have $\mathcal{A}_f^{\Delta\Gamma} = 0$ (the equality is only approximate for quasi-flavour-specific states), while $\mathcal{A}_{J/\psi\, K_S^0}^{\Delta\Gamma} = \cos 2\beta$ to a good approximation in the SM.

However, if the reconstruction and vertexing requirements differ between the two samples, there is potential for systematic biases. An ideal approach is therefore to compare the lifetime distributions of $J/\psi\, K_S^0$ and the topologically similar but flavour-specific final state $J/\psi\, K^{*0}$, with $K^{*0} \to K^+\pi^-$. Since these final states are advantageous for hadron colliders, extremely high statistics will be available in the near future from LHCb (see, for example, Refs. [35, 36]). Note the strong analogy with the measurement of y_D from the comparison of effective lifetimes in $D^0 \to K^+K^-$ and $D^0 \to K^-\pi^+$ [33, 37, 38].

2. *From the difference in effective lifetime between decays to suppressed and favoured final states.*

Another method which has been used to powerful effect to determine charm mixing parameters is the comparison of suppressed ($D^0 \to K^+\pi^-$) to favoured ($D^0 \to K^-\pi^+$) decays [32, 39, 40]. A tagged analysis is needed to disentangle the contributions and maximise the statistical sensitivity. The analogy in the B_d^0 system is the $D^{(*)\pm}\pi^\mp$ final states. However, while the charm system provides efficient and effective tagging using the decay $D^{*+} \to D^0\pi^+$, there is no equivalent for the B mesons. Therefore, this approach does not appear statistically competitive. It is, however, worth noting that terms involving y_d should be considered in order not to bias measurements of the combination of CKM Unitarity Triangle angles $\sin(2\beta + \gamma)$ from these decays [41–44].

3. *From the difference in effective lifetime between CP-even and CP-odd components of self-conjugate vector-vector final states.*

Final states that differ only by having opposite CP-eigenvalues have opposite values of $\mathcal{A}_f^{\Delta\Gamma}$. Hence one possibility is to compare the lifetime distributions between, say, the $J/\psi\, K_S^0$ and $J/\psi\, K_L^0$ final states. An alternative is to use angular analysis to disentangle the components with each CP-eigenvalue in self-conjugate vector-vector final states. This is the approach which is being used to measure $\Delta\Gamma_s$ in $B_s^0 \to J/\psi\, \phi$ decays [45, 46]. The equivalent final state for the B_d^0 is $J/\psi\, K^{*0}$, where the subsequent decay $K^{*0} \to K_S^0\pi^0$ must be used. The requirement on the K^{*0} decay unfortunately complicates the analysis due to the reduced statistics and the less clean final state (note, however, that this decay chain has been used for measurements of $\cos(2\beta)$ [47, 48]). Analyses using $B_d^0 \to D^{*+}D^{*-}$ or $J/\psi\, \rho^0$ are possible but are not particularly attractive from the point of view of statistics.

4. *From the difference in effective lifetime between CP-even and CP-odd components of self-conjugate multibody final states.*

The contributions from amplitudes with each possible CP-eigenvalue for decays to self-conjugate multibody final states can be disentangled using Dalitz plot analysis. However, a tagged analysis is necessary to maximise the statistical sensitivity. In the charm system, such analyses have been carried out using $D^0 \to K_S^0\pi^+\pi^-$ [49–51]. Appropriate channels that correspond to $b \to c\bar{c}s$ transitions include $D^+D^-K_S^0$ and $D^0\bar{D}^0K_S^0$, but the high multiplicity of the final states reduces the available statistics [52]. Larger event yields are or will be available in B_d^0 decay channels such as $K_S^0K^+K^-$ [53, 54], $K_S^0\pi^+\pi^-$ [55, 56] and $D_{CP}\pi^+\pi^-$ (where D_{CP} denotes that the neutral D meson must be reconstructed in a CP eigenstate). However, the lower branching fractions of these decays compared to the $b \to c\bar{c}s$ transitions, as well as the inevitable systematic uncertainties due to Dalitz plot model dependence, make these analyses less attractive for the measurements of y_d. Note, that these final states are, however, interesting for determinations of $\cos(2\beta)$ [57, 58].

The most promising approach to determine $\Delta\Gamma_d$ therefore appears to be from the difference in effective lifetimes between decays to the CP-eigenstate $J/\psi\, K_S^0$ and the flavour-specific final state $J/\psi\, K^{*0}$. If the vertex position is reconstructed identically (specifically, using only the J/ψ decay products, typically $\mu^+\mu^-$) in the two cases then the largest potential source of systematics should cancel almost exactly. Care will be required to ensure that reconstruction and selection requirements on the $K_S^0 \to \pi^+\pi^-$ and $K^{*0} \to K^+\pi^-$ do not induce a bias on the lifetime distributions, but this does not appear to present a significant obstacle to the analysis. Similarly, potential systematic effects due to the different background composition in the two channels should be manageable. One potentially dangerous systematic effect would be an asymmetry, $a_{\rm prod}$, between the production rates of $\bar{B}_d^0$ and B_d^0. If non-zero, the cancellation of terms in Eqs. (4) and (5) will not be exact, so that the untagged rate of Eq. (10) will include an additional factor in the parentheses of $a_{\rm prod}\,(S_f \sin(\Delta m_d \Delta t) - C_f \cos(\Delta m_d \Delta t))$. This can be handled either by fixing $a_{\rm prod}$ based on independent control samples, or by allowing the presence of such a term in the fit to data. Asymmetries in the reconstruction of $J/\psi\, K^{*0}$ events (or direct CP violation in the decay to this final state) would similarly introduce a $\cos(\Delta m_d \Delta t)$ dependence in the lifetime distribution, which can be handled in the same way.

Finally, the approximation of neglecting corrections arising from CP violation in mixing in Eq. 4 and Eq. 5 should be reconsidered. Although this is justified for current analyses (since existing experimental measurements on CP violation in B_d^0–$\bar{B}_d^0$ mixing [4, 5] place much stronger constraints than those on $\Delta\Gamma_d$ [21, 22]), future

precise measurements will need to take both effects into account. Indeed, since the motivation for this study is the possible existence of anomalous CP violation effects, it would clearly be preferable to perform an analysis which allows such terms to be non-zero. The relevant fomulae can be found in Refs. [14, 34] – the effect on the untagged CP eigenstate time-dependent decay rate is similar to that of a production asymmetry indicating the need to determine these parameters from independent measurements.

In summary, the parameter $\Delta\Gamma_d$, which describes the width difference between the eigenstates of the effective weak Hamiltonian in the B_d^0–$\bar{B}_d^0$ system, is of interest to test the Standard Model and potentially to corroborate the recent evidence for anomalous effects in the B system. Few measurements exist, and current experiments have the potential to improve the existing bounds. Further improvement will be possible at the LHCb experiment, where a newly proposed method based on the difference between lifetime distributions for the untagged decays $B_d^0 \to J/\psi\, K_S^0$ and $B_d^0 \to J/\psi\, K^{*0}, K^{*0} \to K^+\pi^-$ appears to be the most promising approach to reach high precision.

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